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Water Bird Diversity as an Indicator of Coastal Health and Pollution: A Narrative Review with SWOT Perspectives

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Abstract

Coastal ecosystems are among the world's most productive environments, supporting fisheries, biodiversity, carbon sequestration, nutrient cycling, shoreline stabilization, and numerous ecosystem services essential for human well-being. However, rapid urbanization, industrialization, land reclamation, agricultural expansion, aquaculture, tourism development, and climate change have accelerated habitat degradation and pollution across coastal regions. These pressures have highlighted the need for reliable biological indicators capable of reflecting ecological conditions beyond conventional physicochemical monitoring. Among vertebrate taxa, water birds have emerged as valuable ecological indicators because they occupy different trophic levels, respond rapidly to habitat alteration, integrate environmental conditions over broad spatial and temporal scales, and are relatively easy to monitor through standardized census techniques. Their diversity, abundance, breeding success, migratory behaviour, and community composition provide important insights into ecosystem integrity, food web stability, habitat quality, and contaminant exposure. This narrative review synthesizes current knowledge on the role of water bird diversity as an indicator of coastal ecosystem health and pollution using a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analytical framework. The review integrates classical ecological theories, biodiversity assessment methods, avian ecology, conservation biology, and recent studies on waterbird monitoring from Southeast Asia and other regions. The strengths of water bird monitoring include high public visibility, cost effectiveness, and ecological relevance, whereas weaknesses include species mobility and natural seasonal variability. Emerging technologies, citizen science, remote sensing, and artificial intelligence offer significant opportunities to improve monitoring programmes; while accelerating coastal development, pollution, habitat fragmentation, invasive species, and climate change remain substantial threats to both water birds and coastal ecosystems. The review concludes that water bird diversity should complement chemical, biological, and habitat assessments within integrated coastal monitoring frameworks to strengthen ecosystem-based management and long-term conservation planning.

Keywords: Coastal Ecosystems; Water Birds; Biodiversity; Biomonitoring; Pollution Indicators; SWOT Perspectives

Introduction

Coastal ecosystems form one of the most biologically productive environments on Earth, functioning as interfaces between terrestrial and marine ecosystems while supporting exceptional biological diversity and numerous ecosystem services. Mangroves, estuaries, tidal mudflats, salt marshes, lagoons, and coastal wetlands provide nursery grounds for fishes, feeding habitats for migratory birds, shoreline protection against erosion, carbon sequestration, nutrient recycling, and water purification. These ecosystems also sustain fisheries, tourism, recreation, and the livelihoods of millions of coastal communities worldwide [1, 2]. Nevertheless, increasing anthropogenic pressures have significantly altered coastal environments during the past several decades. Urban expansion, industrial discharges, agricultural runoff, aquaculture intensification, land reclamation, plastic pollution, heavy metal contamination, and climate change collectively threaten the ecological integrity of coastal habitats, resulting in biodiversity loss and declining ecosystem resilience [3].

Traditional coastal monitoring programmes have largely depended on physicochemical measurements such as dissolved oxygen, nutrient concentrations, salinity, pH, suspended solids, and contaminant concentrations. Although these parameters provide valuable information regarding environmental quality, they often represent only instantaneous conditions and may not adequately reflect cumulative ecological impacts. Biological indicators, in contrast, integrate environmental changes over longer temporal scales and reveal ecological responses that cannot always be detected through chemical analyses alone. Consequently, ecological monitoring has increasingly incorporated biological communities to evaluate ecosystem health, biodiversity status, and environmental sustainability [1, 3, 4].

Among biological indicators, water birds occupy a unique ecological position. They utilize multiple coastal habitats throughout their life cycles, including mudflats, estuaries, mangrove forests, freshwater wetlands, shallow lagoons, and intertidal zones. Their feeding strategies encompass piscivory, herbivory, omnivory, benthic invertebrate predation, scavenging, and filter feeding, allowing different species to represent different components of coastal food webs. Because many water birds occupy relatively high trophic positions, contaminants accumulated by lower trophic organisms may become magnified within bird populations, making them effective indicators of ecosystem contamination, particularly heavy metals, persistent organic pollutants, plastics, and other emerging contaminants [5].

Water birds also respond rapidly to habitat degradation. Reductions in wetland area, mangrove loss, changes in hydrology, shoreline modification, and declining prey availability are frequently accompanied by measurable changes in bird abundance, species richness, breeding success, migration timing, and community composition. Consequently, numerous studies have demonstrated strong relationships between water bird diversity and habitat quality across coastal ecosystems. The ecological requirements of many species make them sensitive indicators of environmental disturbances while simultaneously serving as flagship species for biodiversity conservation and public environmental awareness [6-8].

The scientific foundation for using birds as ecological indicators is supported by decades of ecological research. Species diversity has long been recognised as an important measure of ecosystem complexity and environmental stability [9]. Community ecology further demonstrates that biological communities reflect interactions among environmental filtering, dispersal, competition, and ecological succession [4]. Quantitative measures including species richness, Shannon diversity, Simpson diversity, Sørensen similarity, and beta diversity provide robust approaches for assessing spatial and temporal variation in bird communities [10-12]. Standardized field methods, including point counts, transects, breeding surveys, and habitat assessments, have further improved the reliability of long-term avian monitoring programmes [13, 14].

In tropical regions, particularly throughout Southeast Asia, water birds are increasingly recognized as valuable indicators of wetland condition. Numerous studies conducted in Indonesia have documented the relationships between bird diversity and mangrove quality, protected areas, floodplain habitats, and traditional ecological knowledge [15-20]. These studies collectively demonstrate that habitat heterogeneity, vegetation complexity, hydrological stability, and reduced human disturbance generally support greater water bird diversity. Conversely, habitat fragmentation, wildlife exploitation, and environmental degradation consistently reduce avian diversity while increasing the vulnerability of specialist species. Such findings reinforce the importance of conserving intact coastal habitats to maintain ecological resilience and biodiversity.

The conservation significance of water birds extends beyond ecological monitoring. International initiatives including the International Union for Conservation of Nature (IUCN) Red List and the IOC World Bird List provide standardized taxonomic and conservation frameworks that facilitate global assessments of species status and conservation priorities [21, 22]. Identification of internationally important coastal wetlands increasingly incorporates water bird diversity, abundance, and migratory importance as primary criteria for conservation planning. Long-term monitoring of water bird communities therefore contributes not only to pollution assessment but also to habitat protection, biodiversity conservation, ecological restoration, and sustainable coastal management [23].

Despite increasing recognition of water birds as ecological indicators, important challenges remain. Their high mobility, seasonal migration, and natural population fluctuations complicate the interpretation of monitoring data. Furthermore, no single indicator can adequately represent all dimensions of ecosystem health. Integrating bird diversity with habitat assessments, physicochemical monitoring, contaminant analyses, benthic community structure, and other biological indicators is therefore essential for comprehensive ecosystem evaluation. Recent developments in remote sensing, geographic information systems, citizen science, environmental DNA, artificial intelligence, and automated acoustic monitoring offer promising opportunities to strengthen integrated coastal monitoring programmes while improving spatial and temporal coverage [8].

This narrative review aims to critically evaluate the role of water bird diversity as an indicator of coastal ecosystem health and pollution by synthesizing ecological, conservation, and environmental monitoring literature through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analytical framework. The review further discusses the advantages, limitations, and future directions for incorporating water bird diversity into integrated coastal ecosystem assessment and sustainable environmental management.

Water Bird Diversity as an Indicator of Coastal Health

Coastal ecosystems are characterised by complex ecological interactions among terrestrial, freshwater, and marine environments, making them highly dynamic yet particularly vulnerable to anthropogenic disturbances. Because ecological degradation often manifests through gradual biological responses rather than immediate physicochemical changes, biological indicators have become increasingly important for evaluating ecosystem health. Among vertebrate groups, water birds are widely recognised as effective ecological indicators because they integrate environmental conditions across multiple habitats, occupy diverse trophic levels, and respond sensitively to changes in habitat quality, food availability, hydrological regimes, and pollution levels (Figure 1). Their diversity, abundance, reproductive success, migratory behaviour, and community composition collectively provide valuable information regarding the ecological status of coastal ecosystems [3].

Unlike many aquatic organisms with relatively limited dispersal capabilities, water birds utilise extensive landscapes that encompass estuaries, mangrove forests, mudflats, salt marshes, shallow lagoons, rivers, and coastal wetlands throughout different stages of their

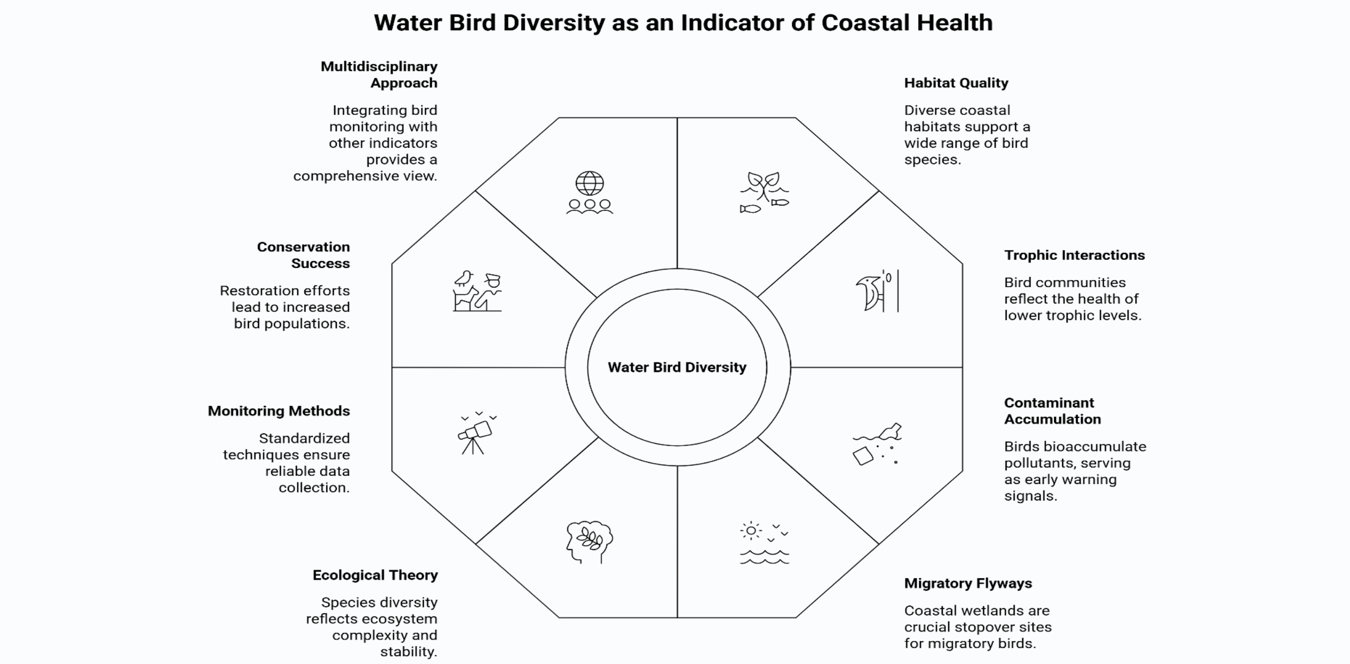

Figure 1: Water bird diversity as an indicator of coastal health.

annual life cycles. Species such as herons, egrets, ibises, ducks, rails, shorebirds, gulls, terns, and kingfishers exploit different ecological niches, allowing bird communities collectively to represent multiple ecological processes occurring simultaneously within coastal ecosystems. Piscivorous species often reflect fish community structure and aquatic productivity, whereas wading birds respond to the abundance of benthic invertebrates inhabiting mudflats and shallow wetlands. Herbivorous and omnivorous species similarly indicate the availability of aquatic vegetation and overall habitat complexity. Consequently, changes in bird assemblages frequently mirror alterations occurring at lower trophic levels, making them valuable integrators of ecosystem condition [24].

One of the greatest advantages of using water birds as ecological indicators lies in their position within food webs. Many species occupy relatively high trophic levels and therefore accumulate contaminants transferred through aquatic food chains. Heavy metals, organochlorine compounds, petroleum hydrocarbons, pesticides, pharmaceuticals, microplastics, and other emerging pollutants can bioaccumulate in aquatic organisms before reaching avian predators through trophic transfer. Consequently, physiological abnormalities, reduced reproductive success, behavioural changes, altered migration patterns, and declining population sizes frequently provide early ecological warning signals that environmental quality has deteriorated. Monitoring water birds therefore complements conventional chemical monitoring by reflecting the biological consequences of contaminant exposure rather than merely measuring contaminant concentrations in water or sediments [5].

Habitat quality represents another fundamental factor linking water bird diversity with coastal ecosystem health. Healthy coastal wetlands typically exhibit high habitat heterogeneity, supporting diverse vegetation communities, stable hydrological conditions, abundant prey resources, and minimal human disturbance. These environmental characteristics create numerous ecological niches capable of supporting a wide range of resident and migratory bird species. Conversely, habitat degradation caused by mangrove deforestation, shoreline armouring, urban development, land reclamation, aquaculture expansion, and industrialisation often simplifies habitat structure, reduces food availability, and disrupts breeding and feeding grounds. Declines in species richness, reductions in specialist species, and increased dominance of disturbance tolerant species frequently accompany such habitat alterations, making community composition an effective measure of ecological integrity [24].

The ecological significance of water birds is particularly evident within migratory flyways. Many coastal wetlands serve as critical stopover, wintering, and breeding sites for migratory species travelling thousands of kilometres annually. The persistence of these migratory populations depends upon the ecological condition of numerous interconnected wetlands across continents. Degradation of even a single staging site may reduce survival, breeding success, or migration efficiency, thereby affecting populations throughout their distributional range. Because migratory water birds integrate environmental conditions across multiple regions, long-term monitoring programmes provide valuable information regarding both local habitat quality and broader ecosystem connectivity. This international perspective has strengthened the inclusion of water bird populations within global conservation initiatives and wetland protection programmes [23].

Ecological theory further supports the application of bird diversity as an indicator of ecosystem health. Classical ecological studies have consistently demonstrated that species diversity reflects ecosystem complexity, environmental stability, and habitat heterogeneity [9]. Community ecology similarly proposes that environmental filtering, dispersal limitation, competition, and stochastic processes collectively determine community composition [4]. Consequently, disturbances that alter habitat structure or resource availability inevitably influence species assemblages. Measures of alpha diversity, beta diversity, species turnover, and community similarity therefore provide

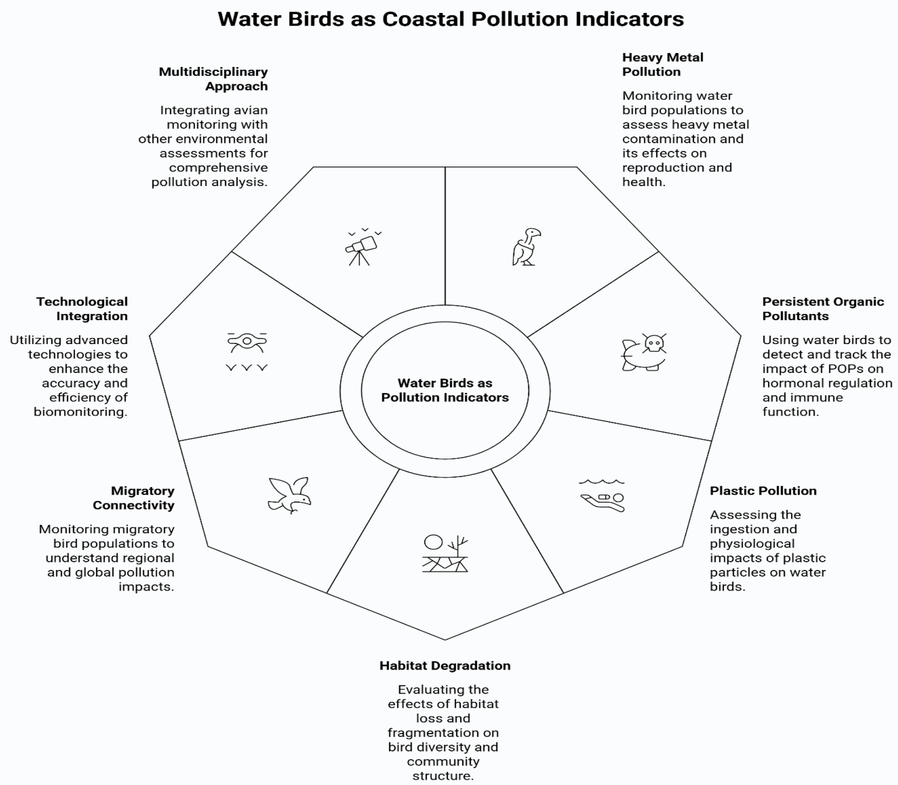

Figure 2: Birds as coastal pollution indicators.

powerful tools for detecting ecological change over time. Diversity indices described by Whittaker [9], similarity measures developed by Sørensen [10], and beta diversity approaches proposed by Koleff *et al.,* [11] remain widely applied in avian ecological studies because they quantitatively capture ecological responses to environmental gradients.

Reliable interpretation of water bird diversity requires standardized survey methodologies that minimise sampling bias and facilitate comparisons across spatial and temporal scales. Point count surveys, line transects, aerial counts, roost surveys, breeding colony assessments, and wetland census techniques have become internationally accepted approaches for monitoring avian communities [13, 14]. These methods provide consistent estimates of species richness, abundance, density, and population trends while allowing integration with habitat mapping, remote sensing, and geographic information systems. Increasingly, automated acoustic recorders, unmanned aerial vehicles, satellite telemetry, environmental DNA, and artificial intelligence assisted image recognition are further improving the efficiency and precision of water bird monitoring programmes [3].

Studies conducted throughout Southeast Asia further illustrate the value of water birds as indicators of coastal ecosystem condition. Investigations in Indonesian mangrove forests, protected wetlands, floodplain ecosystems, and bird conservation areas consistently demonstrate positive relationships between habitat quality and bird diversity. Purify *et al.,* [15] reported that habitat characteristics strongly influenced water bird diversity within mangrove ecotourism areas of Makassar. Similarly, Sulai *et al.,*[19] found that habitat heterogeneity and floodplain dynamics shaped both taxonomic and functional diversity of aquatic and terrestrial bird communities. Studies by Iskandar *et al.,* [17], Putra *et al.,* [16], Putri *et al.,* [18], and Kurnia *et al.,* [20] likewise highlighted the importance of vegetation structure, ecological connectivity, and protected habitats in maintaining avian diversity. These findings collectively demonstrate that bird communities respond consistently to environmental quality across diverse tropical landscapes, reinforcing their suitability as ecological indicators.

Water bird diversity also reflects the effectiveness of conservation and restoration programmes. Restoration of mangroves, salt marshes, and coastal wetlands generally increases habitat complexity, prey availability, and nesting opportunities, resulting in gradual recovery of bird populations. Recent reviews have emphasised that biodiversity indicators, including water birds, should be incorporated alongside ecosystem function indicators such as nutrient cycling, sediment dynamics, and carbon sequestration when evaluating restoration success. Such integrated approaches provide a more comprehensive understanding of ecosystem recovery than structural habitat measurements alone [25].

Nevertheless, water bird diversity should not be interpreted as a standalone indicator of coastal health. Bird populations are influenced by numerous interacting factors, including seasonal migration, climatic variability, reproductive success, predation pressure, disease outbreaks, and regional habitat connectivity. Therefore, robust ecological assessments should integrate avian monitoring with physicochemical analyses, contaminant measurements, benthic macrofaunal communities, fish assemblages, aquatic vegetation, and microbial indicators. Such multidisciplinary monitoring frameworks provide stronger ecological evidence for environmental management while reducing uncertainty associated with reliance on any single biological indicator. This ecosystem-based perspective aligns with contemporary coastal monitoring frameworks that increasingly emphasise multiple complementary indicators for evaluating ecological condition and environmental sustainability [3].

Overall, water bird diversity represents one of the most informative biological indicators available for assessing coastal ecosystem health. Their ecological sensitivity, trophic position, wide habitat utilisation, international conservation significance, and strong public visibility enable them to function as effective sentinels of environmental change. When incorporated within integrated biomonitoring programmes, water birds provide valuable ecological information that supports pollution assessment, biodiversity conservation, habitat restoration, and sustainable coastal management. As anthropogenic pressures on coastal ecosystems continue to intensify worldwide, long-term monitoring of water bird communities will remain an increasingly important component of ecosystem-based environmental assessment and adaptive conservation planning.

Water Birds and Coastal Pollution

Coastal pollution has become one of the greatest environmental challenges affecting aquatic ecosystems worldwide. Rapid industrialization, urban expansion, intensive agriculture, aquaculture, tourism, maritime transportation, and coastal infrastructure development have collectively increased the discharge of contaminants into estuaries, mangroves, lagoons, and coastal wetlands. Pollutants such as heavy metals, petroleum hydrocarbons, pesticides, pharmaceuticals, nutrients, microplastics, and untreated wastewater alter ecological processes at multiple trophic levels, ultimately affecting biodiversity, ecosystem functioning, and ecosystem services. Water birds, because of their close ecological association with aquatic habitats and their positions within coastal food webs, respond to these environmental disturbances through changes in diversity, abundance, reproductive success, physiological condition, and behaviour (Figure 2). Consequently, water bird communities have become increasingly recognised as effective biological indicators for evaluating the ecological consequences of coastal pollution [26].

Unlike physicochemical measurements that provide only instantaneous snapshots of environmental conditions, water birds integrate pollutant exposure over extended temporal and spatial scales. Many species consume fishes, molluscs, crustaceans, insects, aquatic vegetation, or benthic invertebrates that themselves accumulate contaminants from sediments and water. Through trophic transfer, contaminants progressively accumulate within higher trophic organisms, making water birds excellent sentinels of long-term ecosystem contamination. This characteristic is particularly valuable in coastal ecosystems where contaminant inputs fluctuate seasonally with rainfall, river discharge, tidal exchange, and human activities. Biological responses observed in water birds therefore often represent the cumulative ecological impacts of pollution rather than isolated contamination events [5].

Heavy metal pollution remains one of the most extensively studied environmental threats affecting coastal ecosystems. Metals such as mercury, cadmium, lead, arsenic, chromium, copper, zinc, and nickel enter coastal waters through industrial effluents, mining activities, agricultural runoff, municipal wastewater, and atmospheric deposition. Unlike many organic pollutants, heavy metals are not biodegradable and may persist in sediments for decades. Sediments subsequently function as long-term contaminant reservoirs, continuously exposing benthic organisms that serve as prey for numerous water bird species. Elevated metal concentrations have been associated with impaired reproduction, oxidative stress, endocrine disruption, neurological disorders, immune suppression, eggshell abnormalities, reduced hatchability, behavioural alterations, and increased mortality in birds. Monitoring water bird populations therefore provides indirect evidence of contaminant bioavailability and trophic transfer within coastal food webs [5].

The ecological significance of water birds as pollution indicators extends beyond heavy metals. Coastal environments increasingly receive persistent organic pollutants, including pesticides, Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), flame retardants, and pharmaceutical residues. Many of these compounds accumulate within aquatic organisms and bio-magnify through food chains, particularly affecting long-lived piscivorous birds. Chronic exposure may reduce reproductive performance, alter hormone regulation, suppress immune function, and impair embryonic development even when environmental concentrations remain relatively low. Consequently, changes in bird population dynamics frequently provide earlier ecological warning signals than conventional chemical monitoring programmes alone [26].

During the past decade, plastic pollution has emerged as another major environmental concern affecting coastal bird communities. Macroplastics degrade into microplastics and eventually nanoplastics, contaminating sediments, water columns, and aquatic food webs. Water birds ingest plastic particles directly through mistaken prey identification or indirectly via contaminated prey organisms. Ingestion may cause intestinal obstruction, reduced feeding efficiency, nutritional deficiencies, inflammatory responses, and exposure to toxic additives or adsorbed contaminants. Recent reviews have identified birds as effective bioindicators for monitoring plastic pollution because their feeding ecology, mobility, and trophic diversity allow assessment of contaminant distribution across terrestrial, freshwater, and marine ecosystems. Nevertheless, significant knowledge gaps remain regarding nanoplastic exposure, long-term physiological impacts, and species-specific susceptibility [27].

Water pollution also indirectly affects water birds by modifying habitat quality and food resources. Nutrient enrichment from agricultural fertilisers and domestic wastewater often stimulates eutrophication, leading to harmful algal blooms, oxygen depletion, fish mortality, and degradation of submerged aquatic vegetation. Such ecological changes reduce prey abundance and alter habitat suitability for many water bird species. Similarly, sedimentation resulting from land clearing, deforestation, and coastal construction changes benthic community composition, reducing the availability of invertebrates required by shorebirds and wading birds. Declines in species richness under these circumstances therefore frequently reflect ecosystem-wide degradation rather than direct toxic effects of contaminants [24].

Habitat degradation frequently interacts with pollution to amplify ecological impacts on water birds. Mangrove deforestation, shoreline armouring, wetland reclamation, and fragmentation reduce nesting sites, roosting habitats, breeding areas, and migratory stopover locations. Pollution further compounds these habitat losses by reducing prey quality and increasing physiological stress. Consequently, bird communities in degraded coastal landscapes

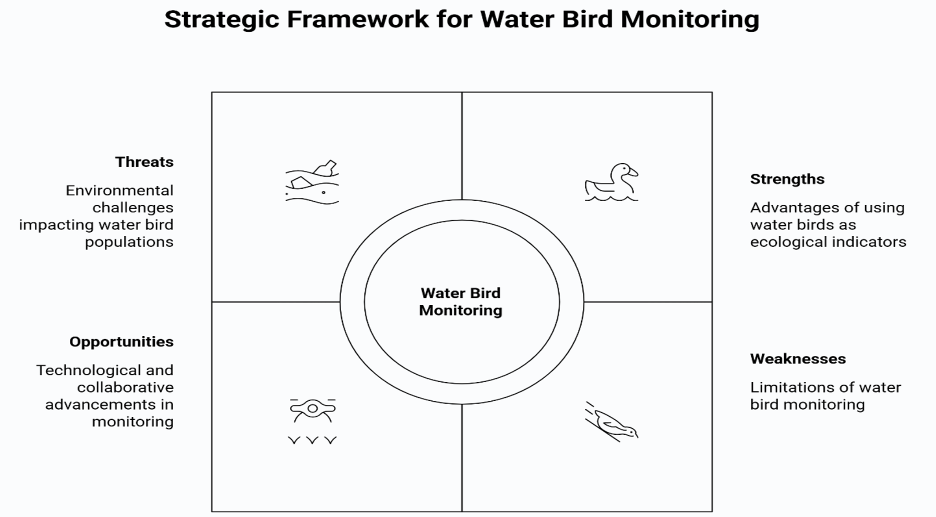

Figure 3: Strategic framework for water bird monitoring.

often exhibit lower diversity, simplified community structure, and increased dominance by pollution-tolerant generalist species. Such community shifts provide valuable ecological evidence of declining ecosystem integrity and resilience [24].

Migratory water birds offer additional value for pollution assessment because they integrate environmental conditions across geographically distant ecosystems. Species travelling along international flyways depend upon multiple coastal wetlands during migration, wintering, and breeding. Pollution or habitat degradation at one staging site may influence survival and reproductive success throughout the migration network. Therefore, long-term monitoring of migratory bird populations provides insights not only into local environmental quality but also into regional and global ecological connectivity. This perspective is increasingly important because pollutants transported through rivers, ocean currents, and atmospheric circulation often transcend political boundaries. International conservation initiatives therefore emphasise coordinated monitoring of migratory water birds as part of ecosystem-based management strategies [28].

Several studies conducted throughout Southeast Asia further demonstrate the relationships between water bird communities and environmental quality. Investigations within Indonesian mangrove ecosystems have shown that bird diversity increases with vegetation complexity, habitat heterogeneity, and reduced human disturbance [15]. Floodplain bird assemblages similarly respond to hydrological variability and habitat structure [19]. Studies on urban landscapes, protected areas, and ecotourism sites have likewise demonstrated that well-managed habitats consistently support greater avian diversity than degraded or fragmented environments [16, 20]. Although many of these investigations primarily focused on habitat characteristics rather than contaminant concentrations, they collectively indicate that bird communities respond predictably to multiple environmental stressors, reinforcing their suitability for integrated coastal monitoring.

Recent advances in ecological monitoring further strengthen the application of water birds as pollution indicators. Satellite remote sensing now enables simultaneous assessment of land use change, shoreline modification, mangrove extent, chlorophyll concentration, turbidity, and wetland dynamics. Citizen science programmes contribute extensive observations of bird distributions across large geographic areas, substantially expanding spatial coverage while reducing monitoring costs. Automated acoustic monitoring, drone surveys, satellite telemetry, artificial intelligence-based image recognition, and environmental DNA analyses provide increasingly powerful tools for integrating biodiversity observations with environmental monitoring. Together, these technologies improve the accuracy, efficiency, and long-term sustainability of coastal biomonitoring programmes [8].

Despite these advantages, interpretation of pollution effects on water birds requires careful consideration of confounding ecological factors. Seasonal migration, climatic variability, prey availability, breeding success, disease outbreaks, predation pressure, and natural habitat succession all influence bird populations independently of pollution. Consequently, declines in abundance should not automatically be attributed solely to contaminant exposure. Robust environmental assessments therefore require integration of avian monitoring with chemical analyses, sediment quality assessments, biomarker studies, benthic community analyses, fish assemblages, habitat evaluations, and hydrological monitoring. Such multidisciplinary approaches provide stronger evidence for identifying pollution sources and understanding ecological mechanisms underlying observed changes in bird communities [25].

Overall, water birds provide a unique bridge between biodiversity conservation and pollution monitoring. Their ecological sensitivity, broad habitat utilisation, trophic positions, international conservation significance, and strong public visibility enable them to serve as effective indicators of coastal environmental quality. However, their greatest value lies not in replacing conventional pollution monitoring but in complementing physicochemical measurements and other biological indicators within integrated ecosystem assessment frameworks. As coastal ecosystems continue to experience increasing anthropogenic pressures, long-term monitoring of water bird diversity will remain an essential component of adaptive coastal management, ecological restoration, pollution control, and sustainable conservation planning.

SWOT Perspectives of Water Bird Diversity as an Indicator of Coastal Health and Pollution

The use of water birds as ecological indicators has gained increasing recognition in coastal ecosystem monitoring because these organisms integrate environmental conditions across multiple trophic levels, habitats, and temporal scales. However, like all biological indicators, their application presents both advantages and limitations. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) perspectives provides a systematic framework for evaluating their effectiveness while identifying future directions for improving coastal biomonitoring programmes (Figure 3). Such an approach is widely applied in strategic environmental planning because it considers both internal characteristics of monitoring systems and external environmental pressures influencing their effectiveness.

Strengths

The greatest strength of water birds as ecological indicators lies in their ability to integrate multiple components of coastal ecosystem health simultaneously. Unlike physicochemical measurements that capture only instantaneous environmental conditions, bird communities respond to long-term changes in habitat quality, prey availability, food web dynamics, hydrological conditions, and contaminant exposure. Consequently, changes in bird diversity often reflect cumulative ecosystem responses rather than isolated pollution events. This ecological integration enables water birds to function as natural indicators of ecosystem integrity while complementing traditional chemical monitoring [3].

Another major advantage is their occupation of different trophic levels within coastal food webs. Water birds include piscivores, insectivores, herbivores, omnivores, scavengers, and benthic invertebrate feeders. Because contaminants are transferred through aquatic food chains, many species accumulate pollutants originating from sediments, water, and lower trophic organisms. This trophic linkage enables bird populations to reflect bioaccumulation and biomagnification processes that are often difficult to evaluate using physicochemical analyses alone. Heavy metals, persistent organic pollutants, and plastics may therefore be detected indirectly through physiological responses, reproductive success, behavioural changes, or population dynamics [5].

Water birds are also relatively easy to monitor compared with many aquatic organisms. Most species are highly visible, identifiable using field guides, and can be surveyed through internationally standardised methods such as point counts, line transects, aerial surveys, and wetland censuses [13, 14]. These approaches require comparatively modest equipment while producing reliable long-term datasets that facilitate comparisons among regions and across decades.

Their ecological importance further strengthens their value as indicators. Water birds depend upon healthy wetlands for feeding, breeding, moulting, and migration. Consequently, declines in species richness, abundance, breeding colonies, or migratory populations frequently indicate degradation of coastal habitats before ecosystem collapse becomes evident. Because many species are protected under national legislation and international conservation agreements, monitoring programmes simultaneously contribute to biodiversity conservation and environmental assessment [23].

Water birds additionally possess considerable educational and public communication value. Birds are among the most familiar wildlife groups to the general public, making monitoring results readily understandable to policymakers, conservation organisations, students, and local communities. Flagship species such as herons, egrets, storks, flamingos, ducks, and migratory shorebirds often stimulate public interest in wetland conservation more effectively than less visible aquatic organisms. Citizen science programmes have therefore become increasingly successful in generating large-scale datasets while promoting environmental awareness [8].

Finally, water bird diversity provides a valuable link between ecological monitoring and ecosystem services. Healthy bird communities often indicate productive fisheries, functioning food webs, stable nutrient cycling, and resilient wetlands. Their conservation therefore indirectly supports sustainable fisheries, ecotourism, carbon sequestration, shoreline protection, and overall human well-being, reinforcing their role as indicators of ecosystem sustainability rather than biodiversity alone [26].

Weaknesses

Despite these strengths, several limitations reduce the reliability of water birds as standalone indicators of coastal pollution. The most important weakness is their high mobility. Many species migrate seasonally or move extensively in response to food availability, weather conditions, and breeding requirements. Consequently, bird abundance at a particular site may change independently of local environmental quality, complicating interpretation of monitoring data.

Seasonal migration represents another important source of variability. Coastal wetlands often support vastly different bird communities between breeding and non-breeding seasons. Without long-term monitoring across multiple seasons and years, temporary fluctuations may be incorrectly interpreted as environmental degradation or recovery. Climatic variability associated with rainfall, tidal cycles, El Niño events, or monsoonal changes may similarly influence bird distributions independent of pollution.

Water bird populations are also affected by numerous ecological variables beyond contamination. Predation, disease outbreaks, habitat competition, invasive species, reproductive success, and regional habitat connectivity all contribute to population dynamics. Consequently, declines in bird diversity cannot automatically be attributed solely to pollution. Interpretation therefore requires complementary information regarding habitat condition, prey communities, hydrology, and environmental chemistry.

Species-specific ecological requirements further complicate monitoring programmes. Generalist species often tolerate disturbed environments and may even increase in abundance following urbanisation, whereas specialist species decline rapidly. Therefore, overall species richness alone may mask important ecological changes unless analyses also consider community composition, functional diversity, and indicator species.

Practical limitations also exist. Comprehensive bird surveys require trained observers capable of accurate species identification, particularly during migration when many morphologically similar species occur together. Observer experience, weather conditions, survey timing, and detection probability introduce unavoidable sampling errors that require standardised protocols to minimise bias [13, 14].

Opportunities

Rapid technological developments provide unprecedented opportunities for improving water bird monitoring and integrating biodiversity with environmental assessment. Advances in satellite remote sensing now enable continuous monitoring of mangrove cover, shoreline change, wetland extent, vegetation productivity, chlorophyll concentration, suspended sediments, and land use dynamics. Combining these environmental datasets with bird observations allows researchers to better understand relationships between habitat change and avian community responses [3].

Artificial Intelligence (AI) offers another transformative opportunity. Machine learning algorithms can automatically identify bird species from photographs, drone imagery, and acoustic recordings, substantially increasing monitoring efficiency while reducing observer bias. Automated image analysis, computer vision, and deep learning technologies are expected to revolutionise large-scale biodiversity monitoring over the coming decade.

Citizen science represents another significant opportunity. Thousands of birdwatchers worldwide regularly contribute observations through online biodiversity platforms, generating extensive datasets across broad geographic regions. These data complement professional monitoring programmes while increasing public participation in conservation. Recent studies have demonstrated that citizen science data can effectively identify water bird dependence on coastal wetlands and improve conservation planning [8].

Environmental DNA (eDNA), stable isotope analysis, telemetry, unmanned aerial vehicles (drones), and bio-logging technologies further enhance opportunities for integrated coastal monitoring. These methods provide information regarding species occurrence, movement ecology, habitat utilisation, migration routes, trophic interactions, and contaminant exposure that was previously difficult to obtain.

International conservation initiatives also create opportunities for collaborative monitoring across migratory flyways. Standardised protocols adopted by the IOC World Bird List, IUCN Red List, Ramsar Convention, and global waterbird census programmes facilitate data sharing among countries, strengthening regional conservation strategies while improving ecosystem assessments.

Perhaps the greatest opportunity lies in integrating water bird monitoring with other ecological indicators. Combining avian diversity with benthic macrofauna, molluscs, fishes, aquatic vegetation, sediment chemistry, microbial communities, remote sensing, and ecological modelling will provide comprehensive ecosystem health assessments that are substantially more informative than any single indicator alone. Such multidisciplinary approaches represent the future of ecosystem-based coastal management [25].

Threats

Despite advances in monitoring technologies, water bird populations continue to face increasing environmental threats that simultaneously reduce biodiversity and complicate ecological assessment. Habitat loss remains the greatest challenge worldwide. Rapid coastal urbanisation, land reclamation, industrial development, tourism infrastructure, aquaculture expansion, and mangrove deforestation continue to eliminate feeding, breeding, and migratory habitats at unprecedented rates [24].

Climate change poses an additional long-term threat through sea level rise, increasing temperatures, altered precipitation patterns, stronger storms, saltwater intrusion, and changing hydrological regimes. These environmental changes alter wetland vegetation, prey availability, breeding habitats, and migration timing, making it increasingly difficult to distinguish pollution effects from climate-driven ecological responses.

Pollution itself continues to diversify. While heavy metals remain important contaminants, emerging pollutants including pharmaceuticals, endocrine-disrupting chemicals, nanoplastics, antimicrobial residues, per- and Polyfluoroalkyl Substances (PFAS), and complex contaminant mixtures present new ecological challenges that remain insufficiently understood. Multiple stressors often interact synergistically, producing biological responses that cannot be explained by single pollutants alone [26].

Biological invasions constitute another growing threat. Invasive plants may alter wetland vegetation structure, whereas invasive fishes and invertebrates modify food web dynamics and prey availability. These ecological changes influence bird communities independently of pollution, further complicating interpretation of monitoring data.

Financial and institutional constraints also threaten long-term monitoring programmes. Sustained ecological monitoring requires continuous funding, trained personnel, standardised methodologies, and political commitment. Many developing countries experience interruptions in monitoring programmes because of limited financial resources, reducing the availability of long-term datasets necessary for detecting gradual ecological change.

Finally, increasing human disturbance from tourism, recreational activities, coastal infrastructure, shipping, and urban expansion places additional pressure on sensitive bird populations. Frequent disturbance reduces feeding efficiency, breeding success, and habitat utilisation, potentially masking or amplifying pollution-related responses. Consequently, successful application of water birds as indicators requires integrated environmental management that simultaneously addresses habitat conservation, pollution control, climate adaptation, and sustainable coastal development.

Overall, the SWOT perspectives demonstrate that the strengths and opportunities substantially outweigh the weaknesses and threats. Water birds remain among the most valuable biological indicators available for assessing coastal ecosystem health. However, their greatest effectiveness is achieved when they are incorporated within multidisciplinary monitoring programmes that integrate biodiversity, ecotoxicology, habitat assessment, remote sensing, and environmental chemistry to provide comprehensive evaluations of coastal ecosystem integrity.

Future Perspectives

The future application of water bird diversity as an indicator of coastal health will increasingly depend on multidisciplinary approaches that integrate ecological monitoring, environmental chemistry, remote sensing, molecular biology, Artificial Intelligence (AI), and ecosystem modelling. Coastal ecosystems are becoming progressively more complex because they are simultaneously affected by pollution, habitat fragmentation, climate change, biological invasions, and increasing human populations. Consequently, future monitoring programmes should move beyond traditional species inventories and adopt comprehensive ecosystem-based assessment frameworks that evaluate biological responses alongside physicochemical, ecological, and socio-economic indicators. Such integrated approaches will provide a more realistic understanding of ecosystem functioning while strengthening conservation and management decisions [3].

One of the most promising developments is the incorporation of artificial intelligence into avian ecological monitoring. Machine learning algorithms can automatically identify bird species from digital photographs, drone imagery, satellite images, and acoustic recordings with increasing accuracy. Automated recognition systems substantially reduce observer bias while allowing continuous monitoring over large spatial scales that would otherwise require considerable human effort. AI can also analyse long-term ecological datasets to identify population trends, migration timing, habitat preferences, and ecological thresholds associated with environmental degradation. Coupled with high-resolution remote sensing, AI has the potential to revolutionise coastal biomonitoring by providing near real-time assessments of both habitat condition and bird community dynamics.

Remote sensing technologies will continue to expand opportunities for large-scale monitoring of coastal ecosystems. Satellite observations can quantify shoreline changes, mangrove deforestation, wetland fragmentation, vegetation productivity, suspended sediment concentrations, chlorophyll levels, sea surface temperature, and coastal land use change. Integrating these environmental datasets with water bird surveys enables researchers to identify ecological relationships that are difficult to detect through field observations alone. Such spatially explicit information is particularly valuable for evaluating habitat connectivity, migratory corridors, and long-term ecosystem resilience under changing environmental conditions [3].

Future biomonitoring should also incorporate emerging molecular approaches. Environmental DNA (eDNA) technologies enable detection of aquatic organisms from water samples without direct collection of individuals, providing information on biodiversity that complements bird observations. Stable isotope analyses can identify trophic relationships and feeding habitats, while contaminant fingerprinting allows identification of pollution sources contributing to contaminant accumulation within coastal food webs. Biomarkers of oxidative stress, endocrine disruption, immune function, and genetic damage may further improve understanding of sublethal pollution effects on water bird populations before visible ecological impacts occur.

Long-term monitoring remains essential for distinguishing natural ecological variability from anthropogenic disturbances. Short-term investigations frequently capture seasonal fluctuations rather than genuine environmental trends. Establishing permanent coastal monitoring stations with standardized survey protocols will enable researchers to evaluate long-term responses to pollution control measures, habitat restoration programmes, and climate adaptation strategies. Standardization of survey methodologies, including point counts, transects, breeding surveys, and migratory bird censuses, will improve comparability among regions while strengthening international collaborations [13, 14].

Citizen science is expected to become an increasingly valuable component of future monitoring frameworks. Advances in smartphone applications, cloud-based databases, and online biodiversity platforms allow birdwatchers and local communities to contribute extensive observations over broad geographic regions. When combined with expert validation and standardized protocols, citizen science substantially expands spatial coverage while reducing monitoring costs. Furthermore, public participation enhances environmental education, increases awareness of coastal conservation issues, and promotes stronger community engagement in wetland protection. Recent studies have demonstrated that citizen science datasets can effectively complement professional surveys for understanding water bird dependence on coastal wetlands and habitat change [8].

Climate change introduces additional challenges that require adaptive monitoring strategies. Sea level rise, altered rainfall patterns, increased storm intensity, ocean warming, and coastal erosion are expected to transform wetland habitats throughout the twenty-first century. Monitoring programmes should therefore evaluate not only current ecological conditions but also ecosystem resilience and adaptive capacity under future climate scenarios. Predictive ecological models integrating climate projections with bird distributions, habitat availability, and pollution dynamics will become increasingly important for conservation planning and ecosystem management [28].

Finally, future coastal health assessments should recognise that no single biological indicator can adequately represent ecosystem condition. Water bird diversity should be integrated with other ecological indicators including benthic macroinvertebrates, molluscs, fishes, aquatic vegetation, phytoplankton, microbial communities, sediment quality, contaminant concentrations, and habitat integrity. Such multidisciplinary frameworks provide stronger ecological evidence than individual indicators while supporting ecosystem-based management consistent with international conservation objectives. This integrated philosophy reflects the growing transition from pollution monitoring toward holistic assessments of ecosystem health and sustainability.

Conclusions

Water bird diversity has become one of the most informative biological indicators for assessing coastal ecosystem health because bird communities integrate environmental conditions across habitats, trophic levels, and temporal scales. Their ecological responses reflect interactions among habitat quality, food availability, hydrological conditions, biodiversity, and contaminant exposure, providing valuable ecological information that complements conventional physicochemical monitoring. Unlike instantaneous chemical measurements, changes in water bird diversity often represent cumulative biological responses to long-term environmental stress, making them particularly valuable for evaluating ecosystem integrity.

The present narrative review demonstrates that water birds possess numerous characteristics that support their application as ecological indicators. Their high trophic positions enable assessment of contaminant bioaccumulation and biomagnification, while their dependence on wetlands makes them sensitive to habitat degradation, pollution, and ecological disturbance. Furthermore, standardized survey methodologies, strong public recognition, and extensive conservation networks facilitate long-term monitoring across regional and international scales. These attributes collectively position water birds as effective sentinels of environmental change within coastal ecosystems.

The SWOT perspectives further highlight that the strengths of water bird monitoring substantially outweigh its limitations. Strengths include ecological sensitivity, trophic integration, monitoring practicality, and conservation relevance. Weaknesses primarily arise from species mobility, seasonal migration, and the influence of multiple environmental variables beyond pollution. Nevertheless, rapid advances in artificial intelligence, remote sensing, environmental DNA, automated acoustic monitoring, and citizen science provide unprecedented opportunities to strengthen monitoring programmes while expanding spatial and temporal coverage. Conversely, accelerating habitat loss, pollution, climate change, biological invasions, and insufficient long-term monitoring remain significant threats that require coordinated conservation efforts.

Importantly, the review emphasises that water birds should not be regarded as standalone indicators of coastal pollution. Instead, they should form one component of multidisciplinary ecosystem assessment frameworks that integrate biological, chemical, physical, and socio-economic indicators. Such integrated monitoring provides more robust evidence for environmental decision-making while reducing uncertainty associated with reliance on any single indicator. Future coastal management should therefore adopt ecosystem-based monitoring strategies that simultaneously evaluate biodiversity, habitat integrity, ecosystem functions, and contaminant dynamics.

Ultimately, conserving water bird diversity is inseparable from conserving healthy coastal ecosystems. Protecting wetlands, mangroves, estuaries, tidal flats, and other coastal habitats will not only sustain bird populations but also preserve fisheries, maintain biodiversity, enhance carbon sequestration, support coastal livelihoods, and strengthen ecosystem resilience against future environmental change. Water birds therefore represent far more than charismatic wildlife; they are living indicators of the ecological condition of coastal environments and valuable sentinels guiding sustainable management of one of the planet's most productive and vulnerable ecosystems.

Declaration on the Use of Artificial Intelligence

The author declares that generative artificial intelligence tools were used in a supportive capacity during the preparation of this manuscript. These tools assisted with language refinement, structural organisation, and stylistic clarity of the text. All ideas, interpretations, reflections, and conclusions presented in this paper are the author's own and are grounded in personal experience and scholarly judgment. The author retains full responsibility for the content, accuracy, originality, and integrity of the manuscript.

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